One Dimensional Analysis Model of a Condensing Spray Chamber Including Rocket Exhaust Using SINDA/FLUINT and CEA

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Facility and Exhaust System Description

Figure 1: Aerial View of Spacecraft Propulsion Research Facility (B-2)

- Constructed in the 1960s, primarily to support the Centaur upper stage development
- Provides the facilities to simulate a space thermal soak and subsequent altitude firing of an engine propulsion system

Facility and Exhaust System Description

- The facility is sized for hydrogen-oxygen engines up to 445 kN (100,000 lbf) thrust
- Thermal simulation is provided on the cold end by a liquid nitrogen cold wall.
- Engine exhaust products enter a spray chamber which cools and condenses the exhaust through 224,000 gpm of spray water.
- To maintain vacuum conditions during engine firing, there is a steam ejector system to transport the remaining exhaust products (hydrogen) to the atmosphere.
- Spray chamber should not exceed about 1.1 psi.

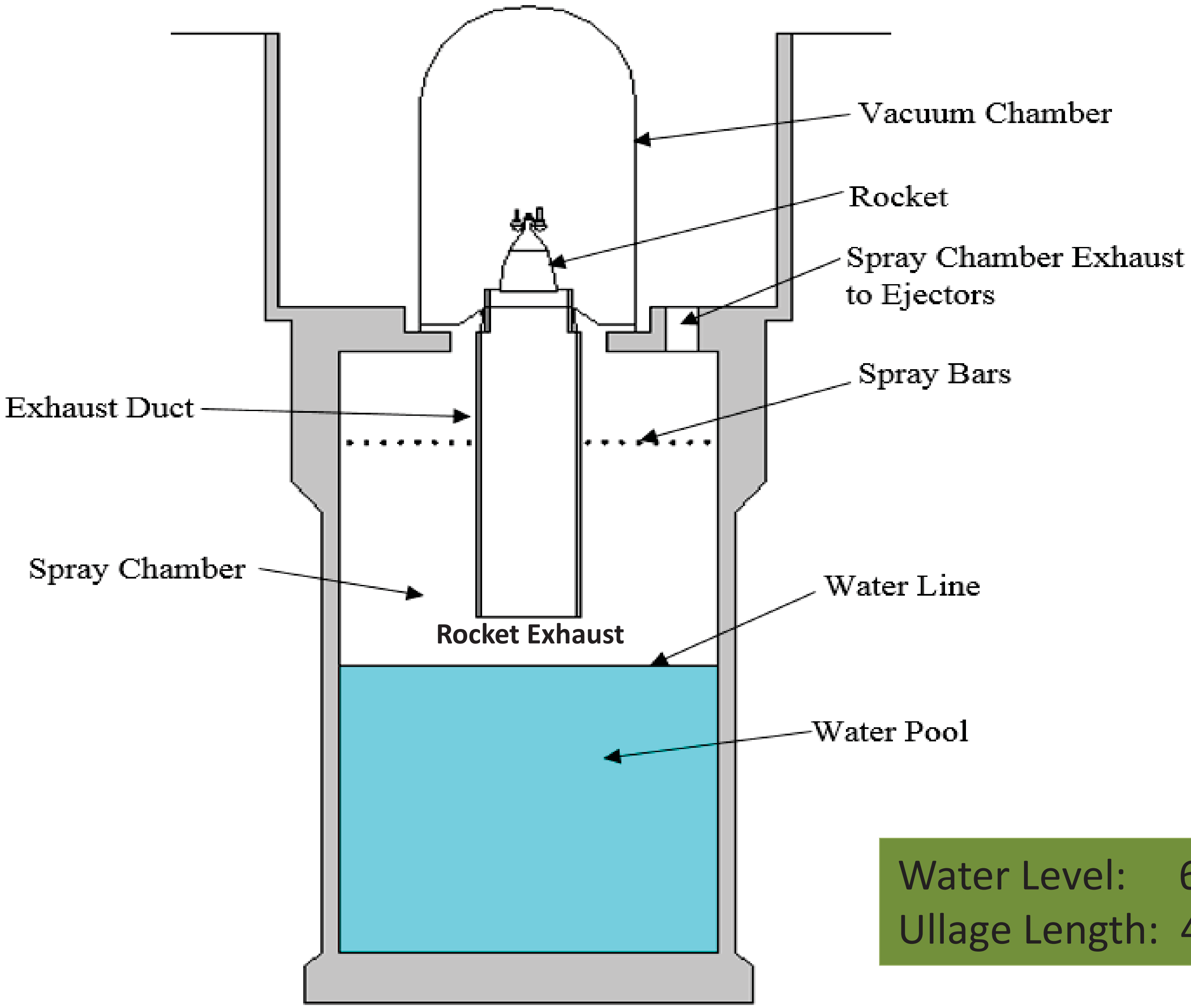
Executive Summary

- CFD codes:
  - Time consuming (particle tracking)
  - Inaccurate (can't do condensation very well with noncondensibles)
  - Too cumbersome to model integrated system (wall heat transfer, ejecter pumping system)
  - Don't take into account droplet conduction – WHY!
    - It is hypothesized that given the droplet sizes (on the order of 1500 microns and greater), droplet velocities (on the order of 37 m/s), and size of the spray chamber, that the water droplets may not be fully utilized.

Executive Summary

- The goals of the analysis tool:
  - Transient one dimensional flow and heat transfer
  - **ALL INCLUSIVE**
    - Rocket combustion
    - Rocket duct flow with wall heat transfer
    - Rocket shock and quench,
    - Condensing spray chamber
    - Ejector pumping system
  - Include droplet conduction
  - Include degrading effects of mass and heat transfer due to the presence of noncondensibles
  - Make no presupposition on the condensation efficiency of the spray chamber
  - Compare results to the RL-10 engine pressure test data.

Facility and Exhaust System Description



Water Level: 67-74 ft
Ullage Length: 45.6 ft

Figure 2: B2 Facility

Facility and Exhaust System Description

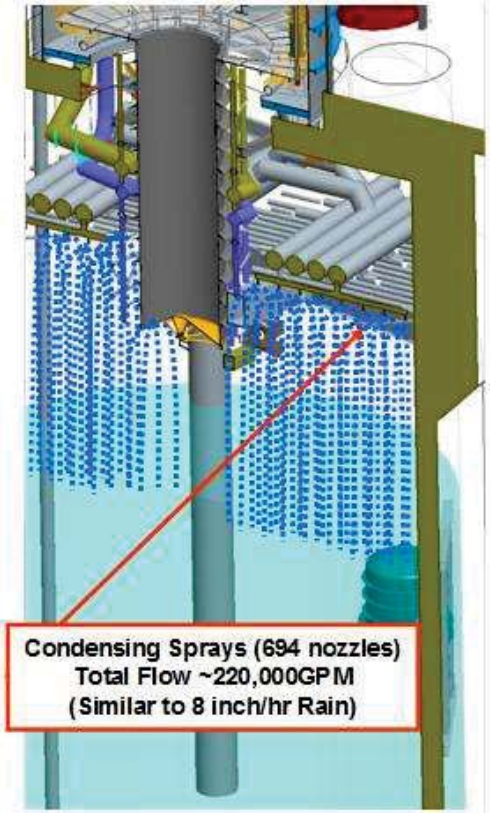
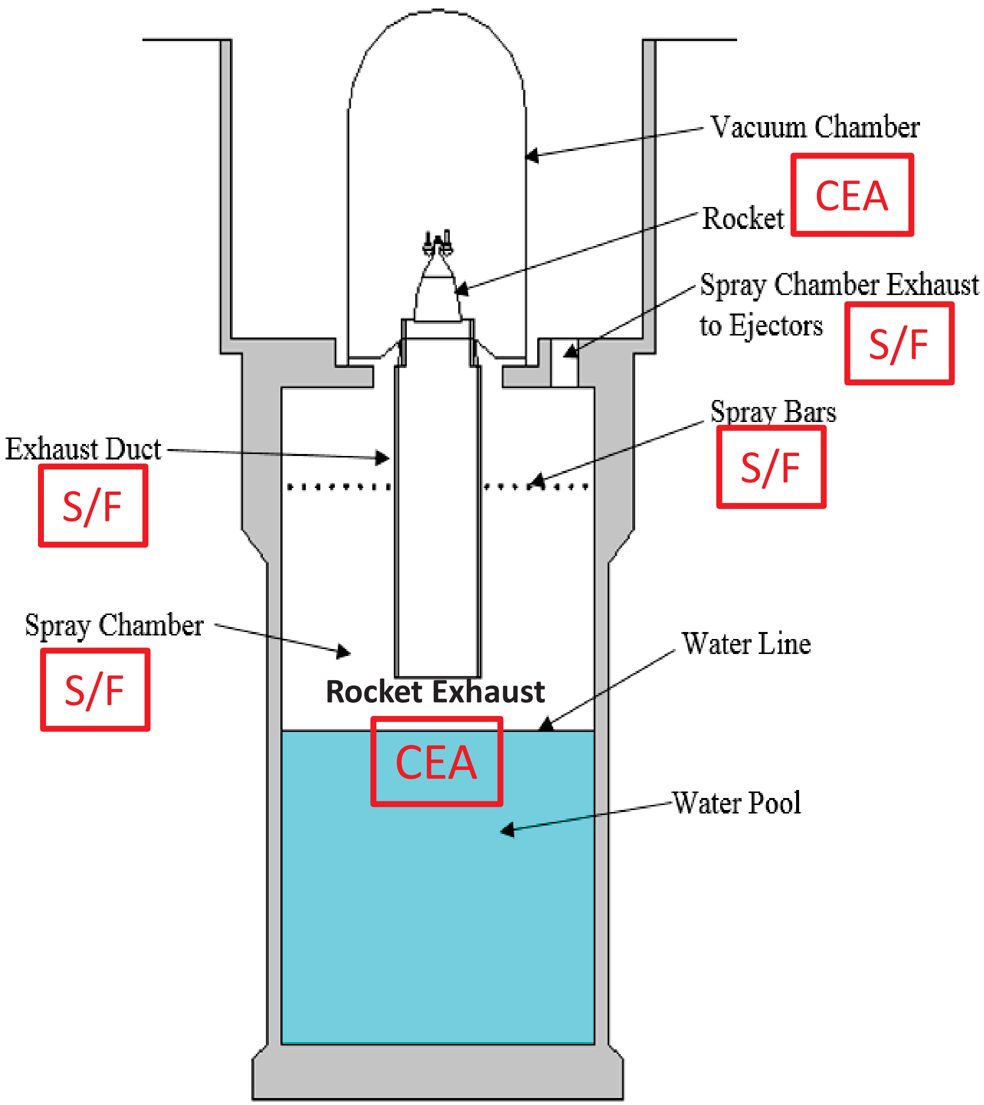


Figure 3: Condensing Spray System

Facility and Exhaust System Description

Figure 4: Condensing Spray System with Ejectors

Facility and Exhaust System Description



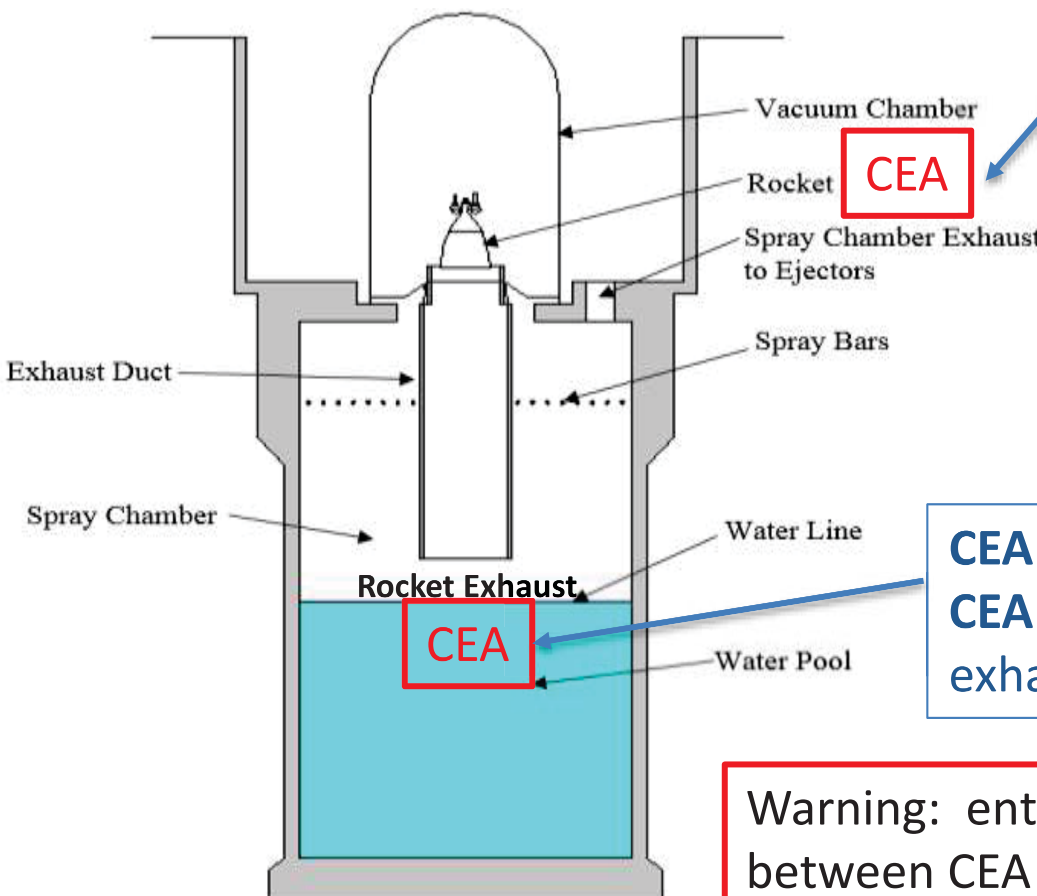
S/F: SINDA/FLUINT

CEA: Chemical Equilibrium with Applications

- CEA (SINDA/FLUINT Subroutine)
  - Rocket Combustion
  - Rocket Exhaust: Shock & Quench
- SINDA/FLUINT
  - Duct Flow (Supersonic!!!!)
  - Duct Wall Heat Transfer
  - Spray Chamber
  - Ejector Pump System
  - Fortran Coding of Droplet Tracking
  - Droplet Conduction

SINDA/FLUINT CEA Modeling Applications

- CEA, Chemical Equilibrium with Applications, is a NASA developed code that calculates mixture chemical equilibrium compositions and properties. The source code is written in ANSI standard FORTRAN, and is appended as a subroutine to the SINDA/FLUINT model of the B2 facility.



CEA is run as an enthalpy/pressure case (input O/F, area ratios)
CEA calculates mass flow rate, temperature and pressure (input to S/F)
CEA is also used to determine duct flow stagnation properties

CEA determines post shock conditions
CEA determines quenched conditions exhaust after shock

Warning: enthalpy and entropy reference states differ between CEA and S/F!!!

SINDA/FLUINT Model Setup

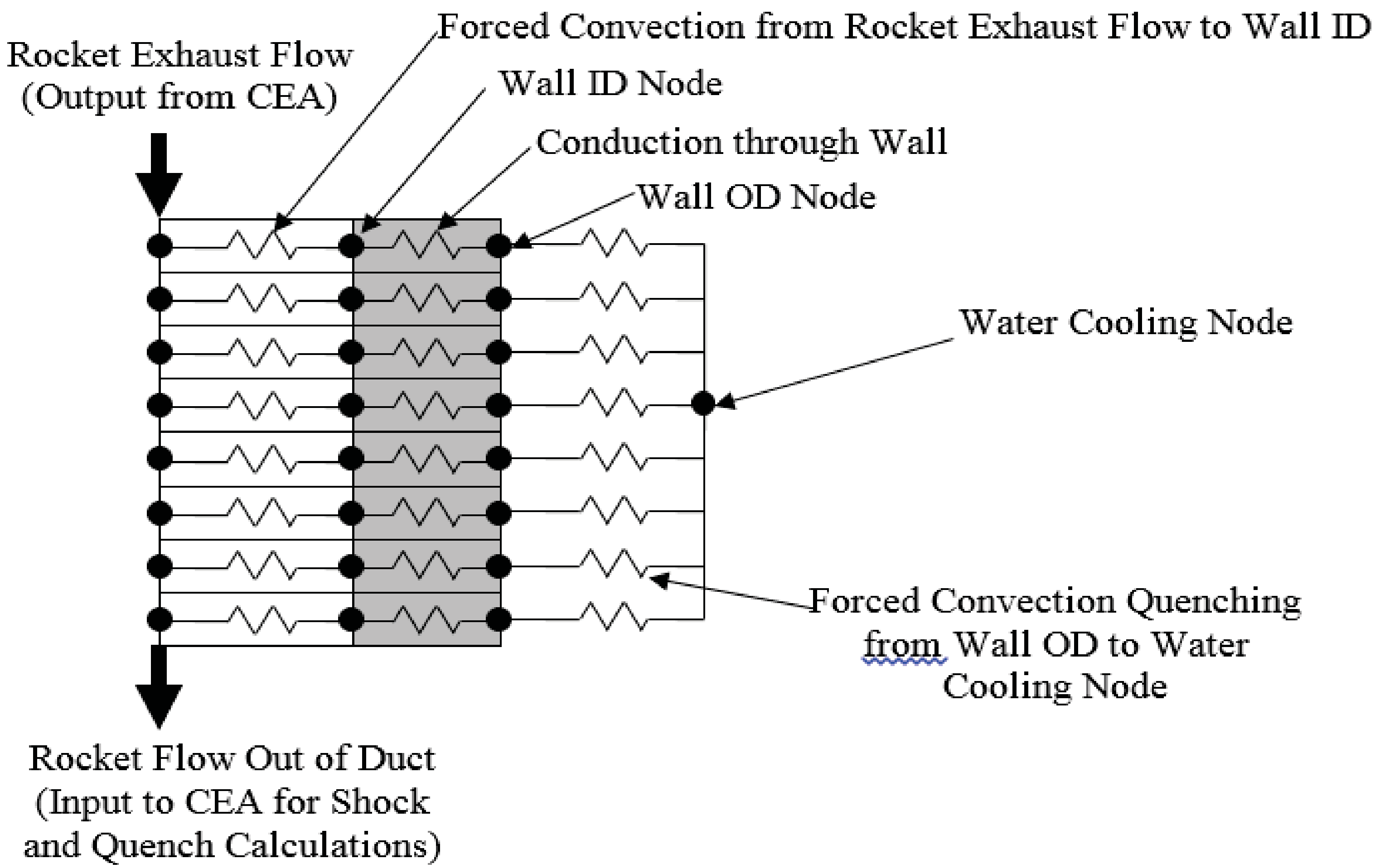


Figure 5: SINDA/FLUINT Submodel "A" of Rocket Exhaust Duct

SINDA/FLUINT Model Setup

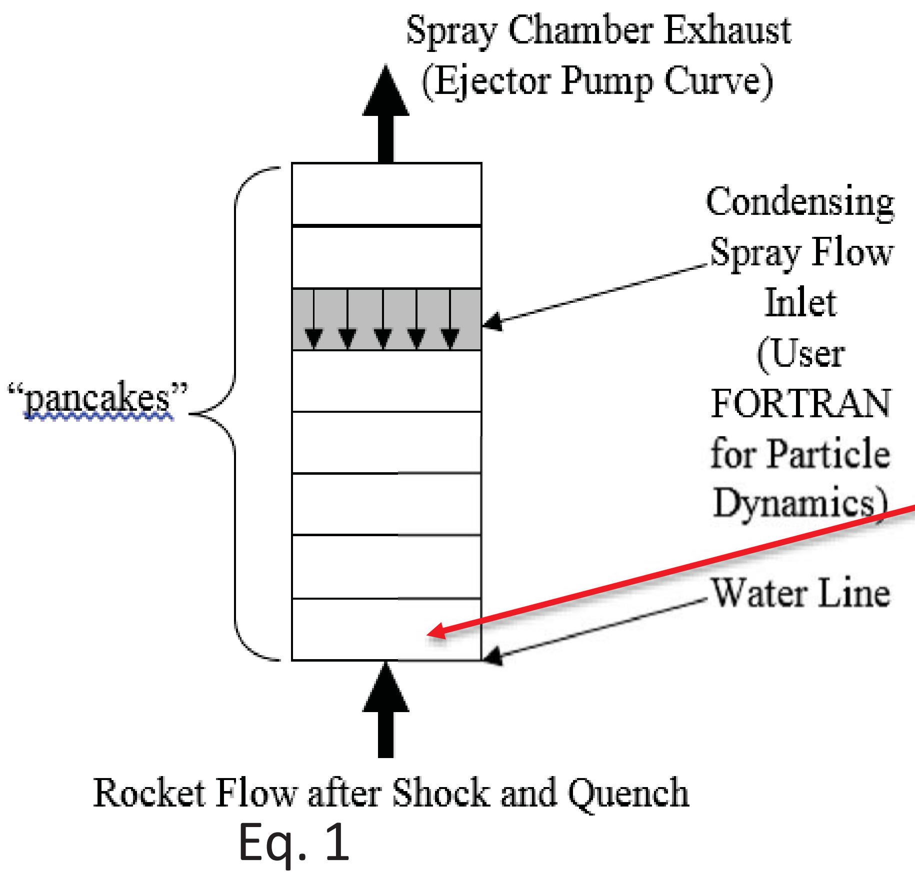


Figure 6: SINDA/FLUINT Submodel "B" of Spray Chamber

Eq. 1 $G_n = 4\pi k_d \frac{r_n r_{n-1}}{r_{n-1} - r_{n-1}}$ Droplet Conductor

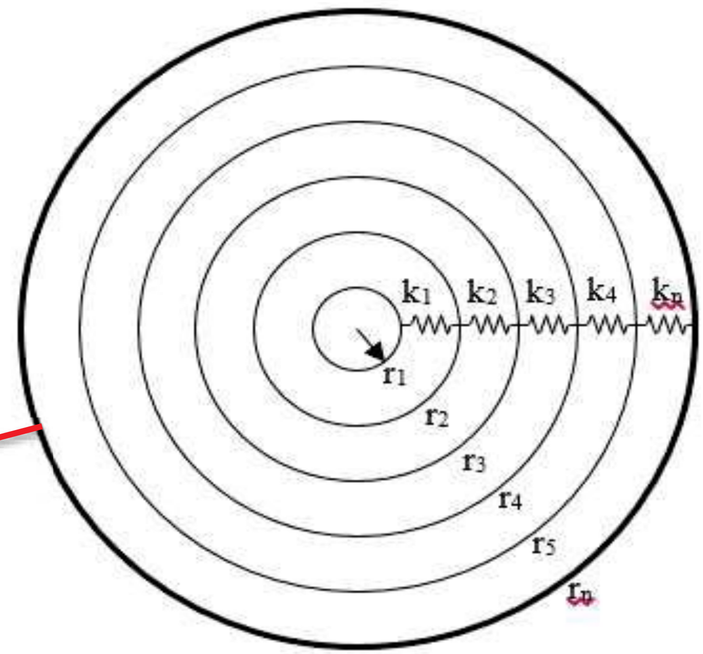


Figure 7: SINDA/FLUINT Submodel "C" of Thermal Conduction in Droplet

SINDA/FLUINT Supersonic Flow Modelling

- The rocket exhaust duct flow or duct entrance flow is supersonic (Mach = 6 to 7)
- **Five** significant issues need to be addressed:
  - **First**, a FLUINT set mass flow rate connector (MFRSET), is placed at the duct exit.
  - **Second**, all choking calculations must be turned off in FLUINT.
  - **Third**, set **IPDC=0** for the FLUINT connectors, i.e., duct friction calculations are supplied by the user.
    - FLUINT does not evaluate fluid properties at a reference temperature in calculating friction factors:

Eq. 2 $$T_{ref} = 0.5(T_{wall} + T_{fluid}) + 0.22(T_{rec} - T_{stat})$$

Eq. 3 $$T_{rec} = Pr^{1/3}\,(T_{stag} - T_{stat}) + T_{stat}$$

SINDA/FLUINT Supersonic Flow Modelling

- Set **FC** as positive (usually negative), **FPOW = 1**:

SINDA/FLUINT Momentum Equation

Eq. 4
$$\frac{dFR_k}{dt} = \frac{AF_k}{TLEN_k}\left(PL_{up} - PL_{down} + HC_k + \boxed{FC_k \cdot FR_k \cdot |FR|_k^{FPOW_k}} + AC_k \cdot FR_k^2 - \frac{FK_k \cdot FR_k \cdot |FR|_k}{2 \cdot \rho_{up} \cdot AF_k^2}\right)$$

Eq. 5
$$FC = \frac{F}{2Ac_D^2\rho}$$

Eq. 6
$$F = 0.184\,Re^{-0.2}\,\frac{L_D}{D_D}$$

SINDA/FLUINT Supersonic Flow Modelling

– **Fourth,** supply a turbulent heat transfer coefficient is calculated with fluid properties evaluated at T_{ref} using the Colburn Analogy:

Eq. 7 $$h_D = 0.23 Re^{0.8} Pr^{1/3} \frac{k}{D_D}$$

SINDA/FLUINT Supersonic Flow Modelling

- **Fifth**, check velocity limit on the kinetic energy term in the total enthalpy energy equation
  - The FLUINT maximum velocity constraint in this analysis was 3000 m/s (SINDA/FLUINT version 5.3). **This constraint did not allow for the conservation of total enthalpy for adiabatic flow.**
  - **Cannot necessary change to as high as you want!!!** (3700 m/s max)
  - To “conserve” total enthalpy impose heat rates on fluid lumps representing the duct flow:
    - the “pseudo” kinetic energy term that’s missing because of the velocity limit.

SINDA/FLUINT Model Details of Spray Chamber

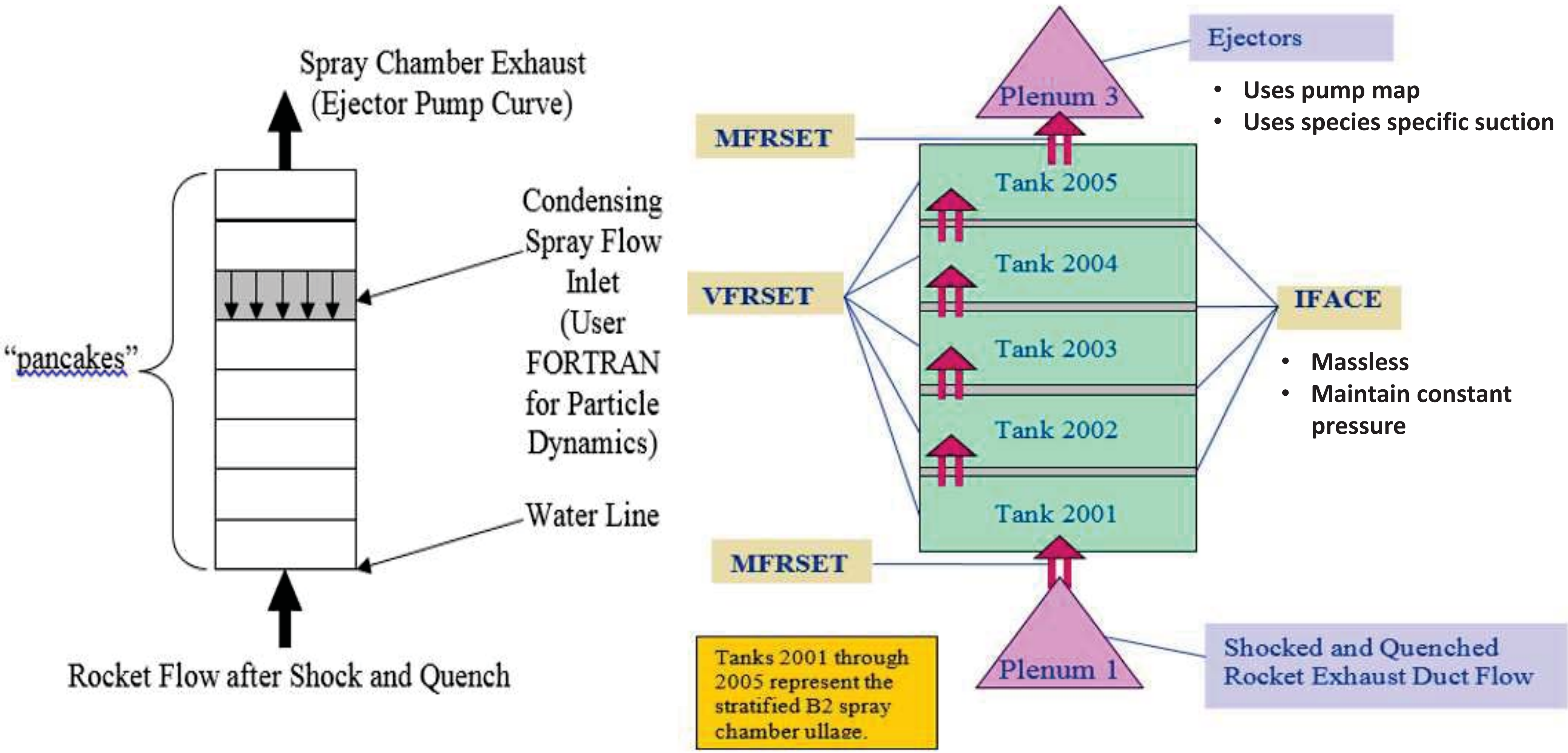


Fig 10: SINDA/FLUINT Submodel "B" of Spray Chamber

SINDA/FLUINT Model Details of Spray Chamber

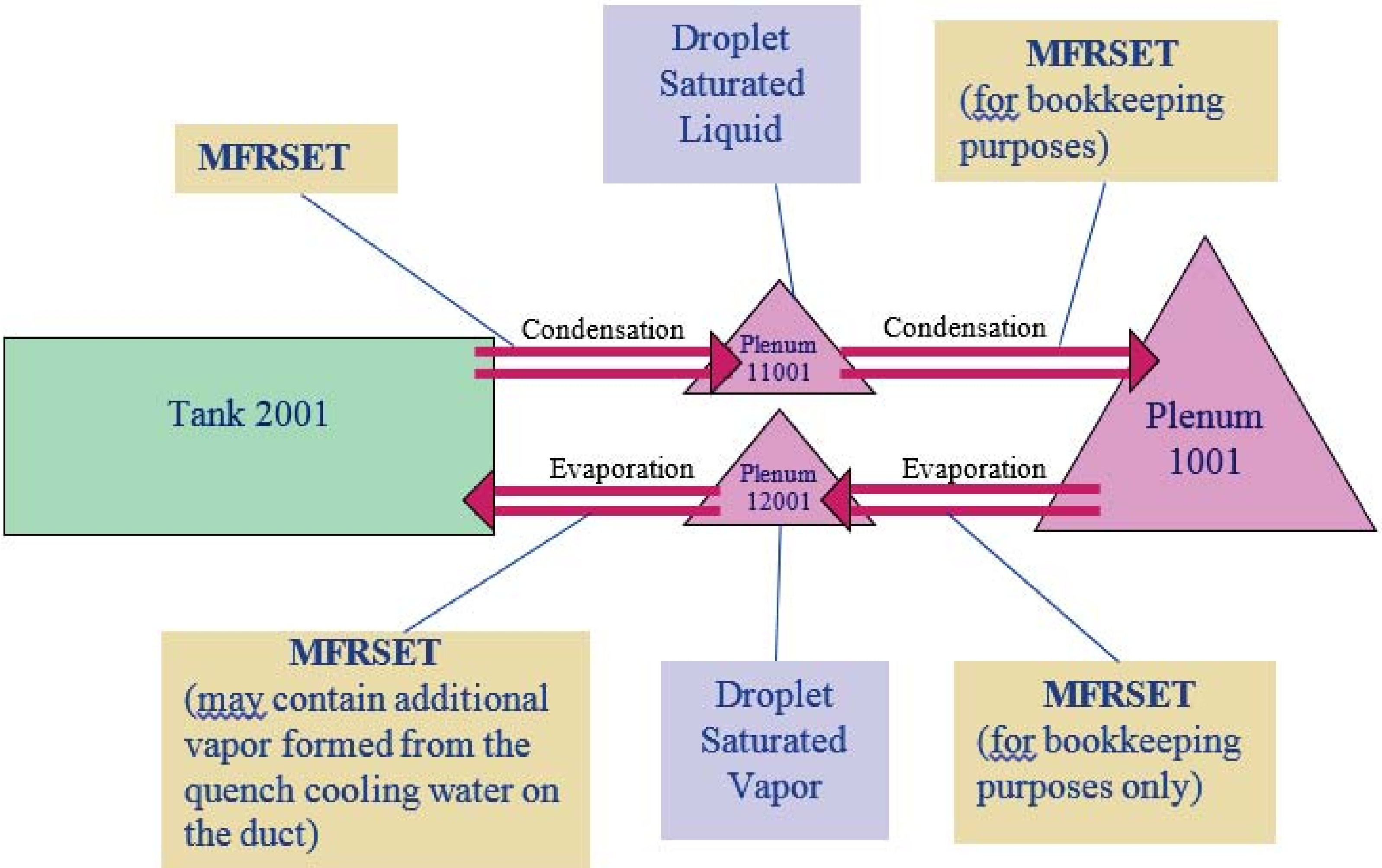
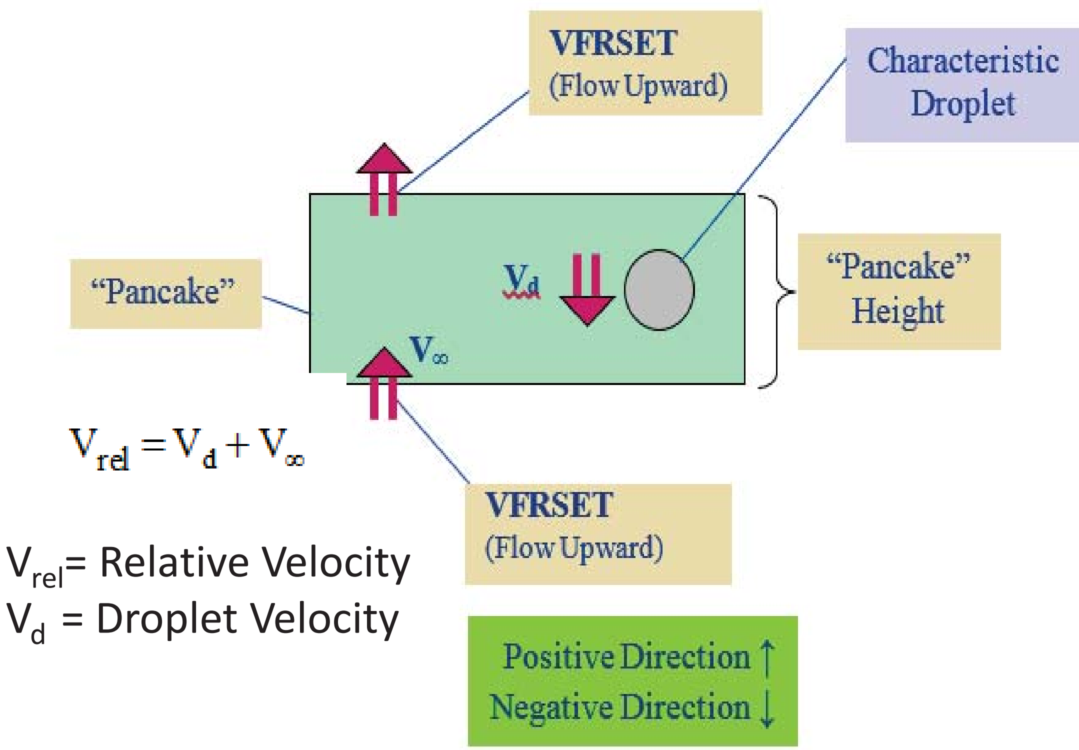


Figure 11: SINDA/FLUINT Lump Detail

SINDA/FLUINT Model Details of Spray Chamber Droplets

Droplet Movement:

- FORTRAN coded droplet tracking
- Individual droplets are not tracked
- Characteristic droplet per "pancake"
- Time averaged value of velocity and temperature distribution must be determined for each "pancake"
- Droplets only move downwards



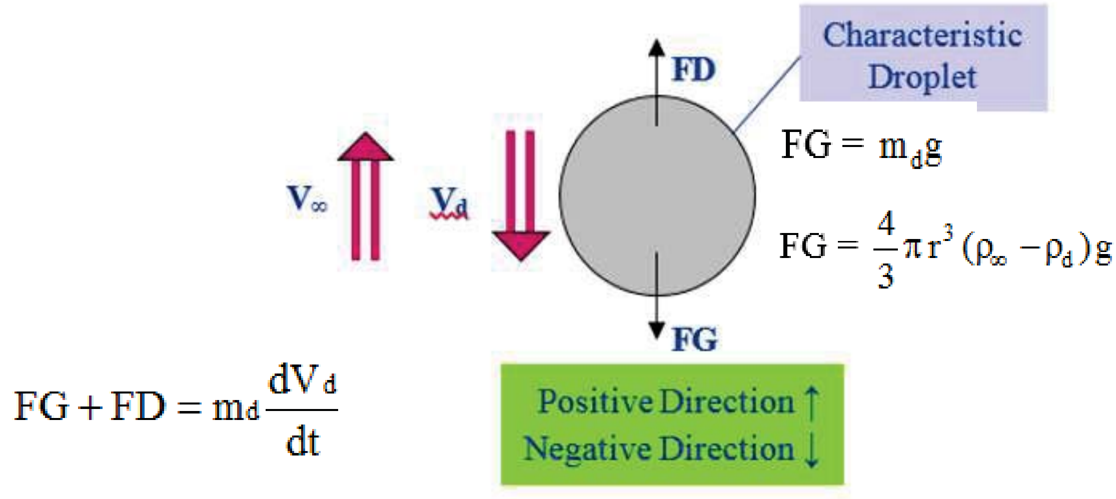


Figure 12: Characteristic Droplet in SINDA/FLUINT Stratified Lump or "Pancake"

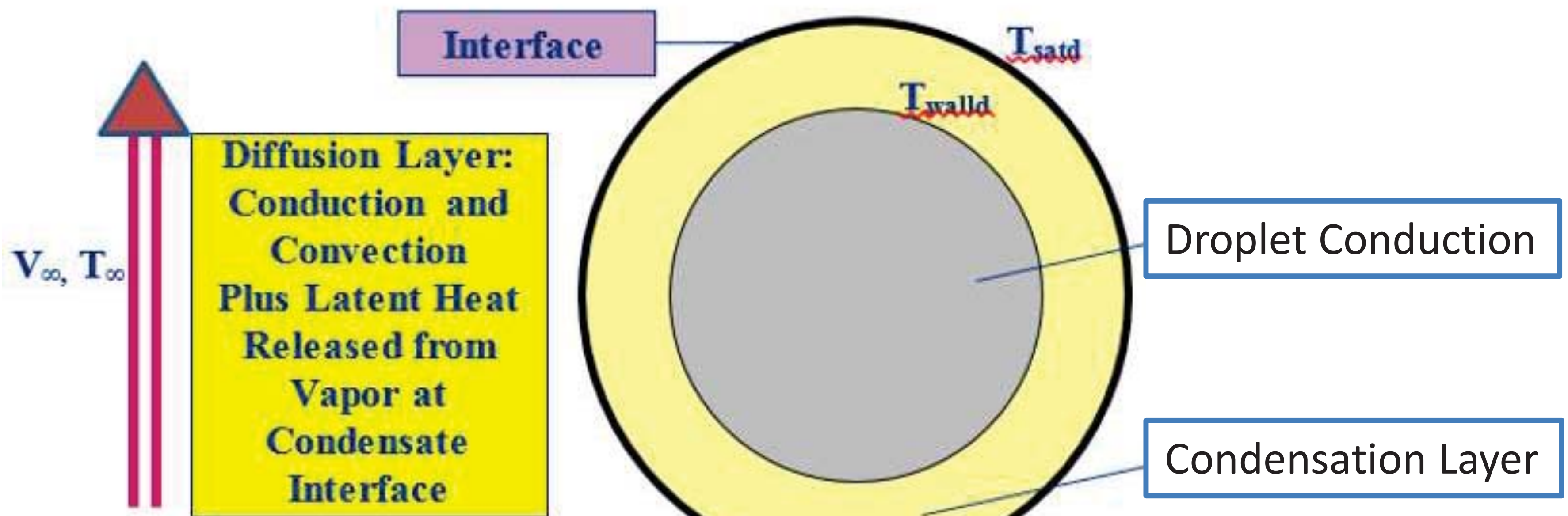
SINDA/FLUINT Model Details of Spray Chamber Droplets

- **Flooding or Floating**!
  - If there is a net upward force – droplets go into a “holding” pattern in their “pancake”
  - Droplets do not experience flow reversal – too complex
  - Droplets from a “pancake” above with a net downward force can still enter
  - If the net force becomes downward again – all droplets travel enmasse to the “pancake” below

SINDA/FLUINT Model Details of Spray Chamber Droplets

Droplet Heat Transfer with Noncondensables:

- During condensation the noncondensable accumulates at the surface (its partial pressure increases)
- This diffusion barrier:
  - decreases mass transfer of water vapor
  - reduces the saturation temperature at which condensation occurs



Ranz Marshall

$$Nu = 2.0 + 0.6\,Re^{0.5}\,Pr^{0.33}$$

Figure 13: Droplet Heat Transfer

SINDA/FLUINT Model Details of Spray Chamber Droplets

- **SINDA/FLUINT SUBROUTINE HTUDIF**:
  - returns, h_{eff}, the effective condensation heat transfer coefficient, including the effect of the noncondensible
  - Requires the uncorrected film condensation heat transfer coefficient AND the convection heat transfer coefficient
  - Can calculate the interface temperature (corrected saturation temperature of droplet)
  - uses the Chilton-Coulburn analogy:

Eq. 8

$$\frac{h_{conv}(\rho_{w\infty}-\rho_{wi})}{m''_{w}} = \left[\frac{P_{tot}}{P_{h\infty}}\rho_{h\infty}\frac{\ln\left(\frac{\rho_{hi}}{\rho_{h\infty}}\right)}{(\rho_{hi}-\rho_{h\infty})}\right]^{-1}\left[\rho_{\infty}\,Cp_{\infty}\left(\frac{k_{\infty}}{D_{wh}}\right)^{2}\right]^{1/3}$$

Validation Cases

- Model results were compared to Delta III upper stage hot fire tests that were run in the B2 facility.
- In all the cases presented below the droplets leaving the spray bar were 1500 microns in size and had an initial velocity 37 ft/sec.

Validation Cases

	HOT FIRE 3	HOT FIRE 6	HOT FIRE 8	HOT FIRE 10
CONDENSING SPRAY CONDITIONS				
INLET CONDENSING SPRAY TEMPERATURE (DEG F)*	50.6	51.5	55.99	64.2
INLET CONDENSING SPRAY FLOW RATE (KG/SEC)	13878	13878	13878	13878
WATER LEVEL (FT)	67.8	73.8	73.6	64.5
ULLAGE LENGTH (FT)	45.65	45.65	45.65	45.65
ROCKET CONDITIONS				
ROCKET EXIT AREA (IN^2)	1500	1500	1500	1500
ROCKET AREA RATIO	77	77	77	77
ROCKET O/F RATIO	6	6	6	6
ROCKET COMBUSTION PRESSURE (PSI)	640	640	640	640

* *For spray bar temperature rise due to engine heat exhaust or ejector heat output this was only an initial condition.*

Figure 14: Summary Table of Delta III Upper Stage Hot Fire Tests

Delta III Upper Stage Hot Fire Test and SINDA/FLUINT

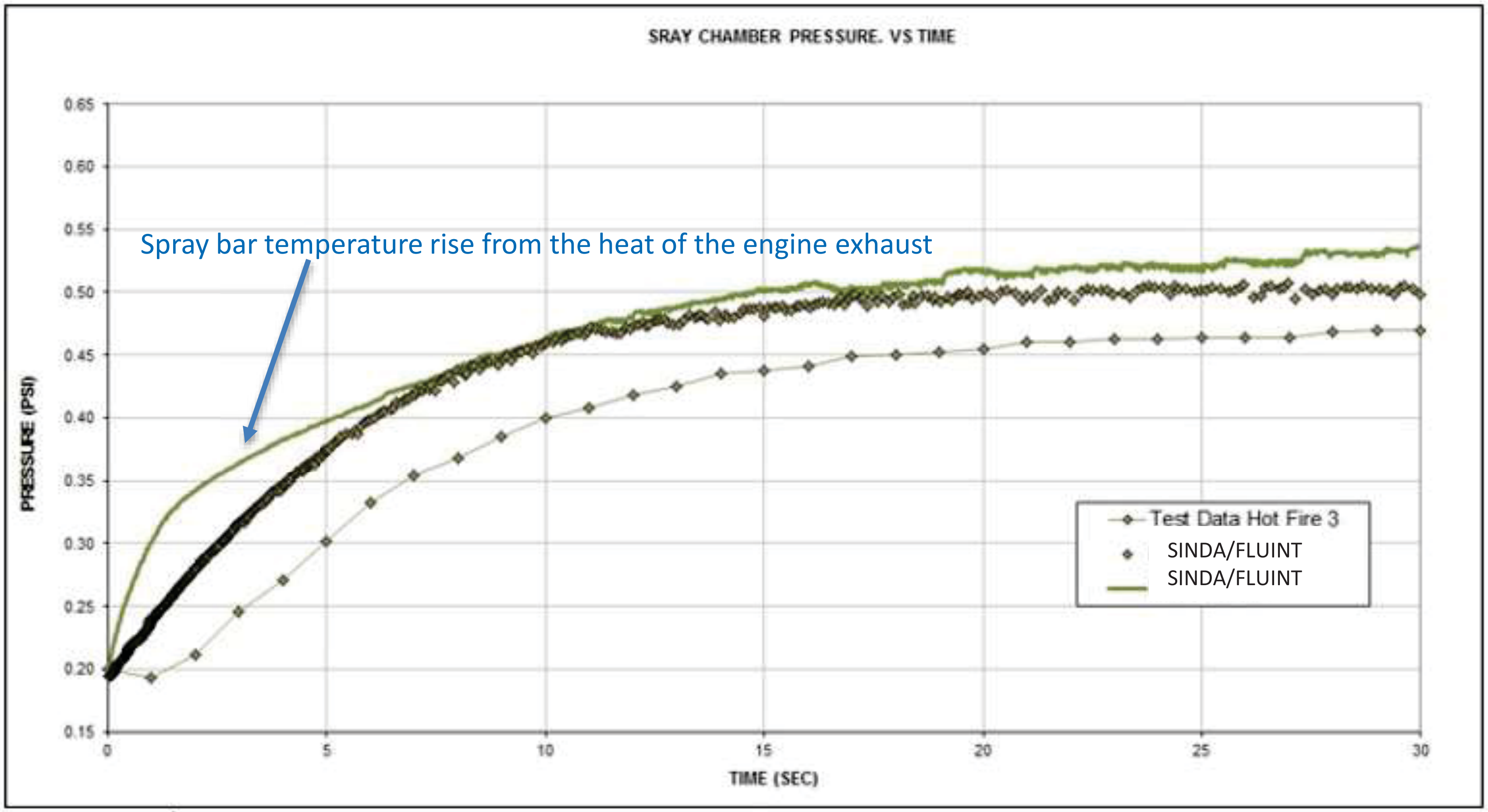


Figure 15: Spray Chamber Pressure: Hotfire Test 3 and SINDA/FLUINT Model Results

Delta III Upper Stage Hot Fire Test and SINDA/FLUINT

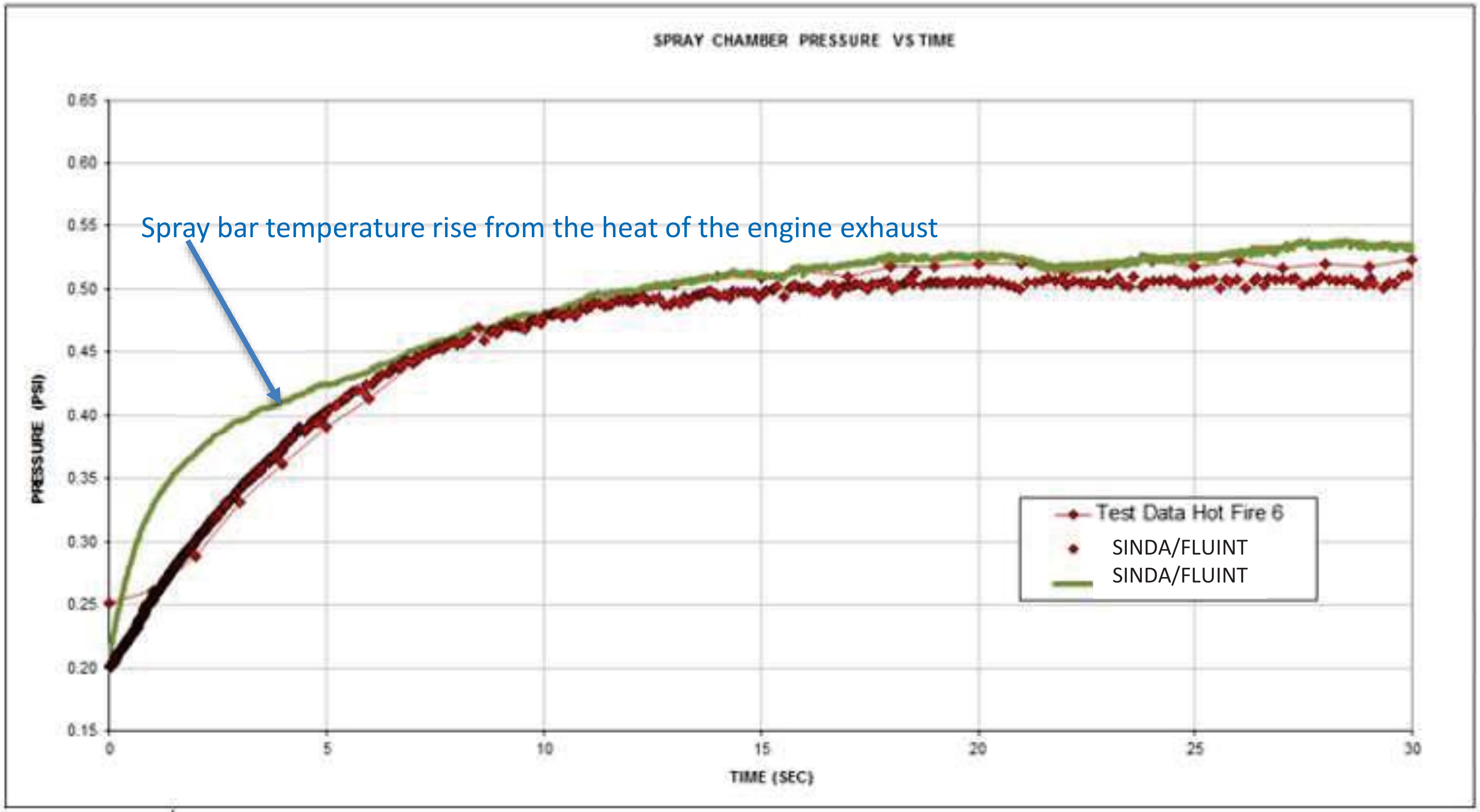


Figure 16: Spray Chamber Pressure: Hotfire Test 6 and SINDA/FLUINT Model Results

Delta III Upper Stage Hot Fire Test and SINDA/FLUINT

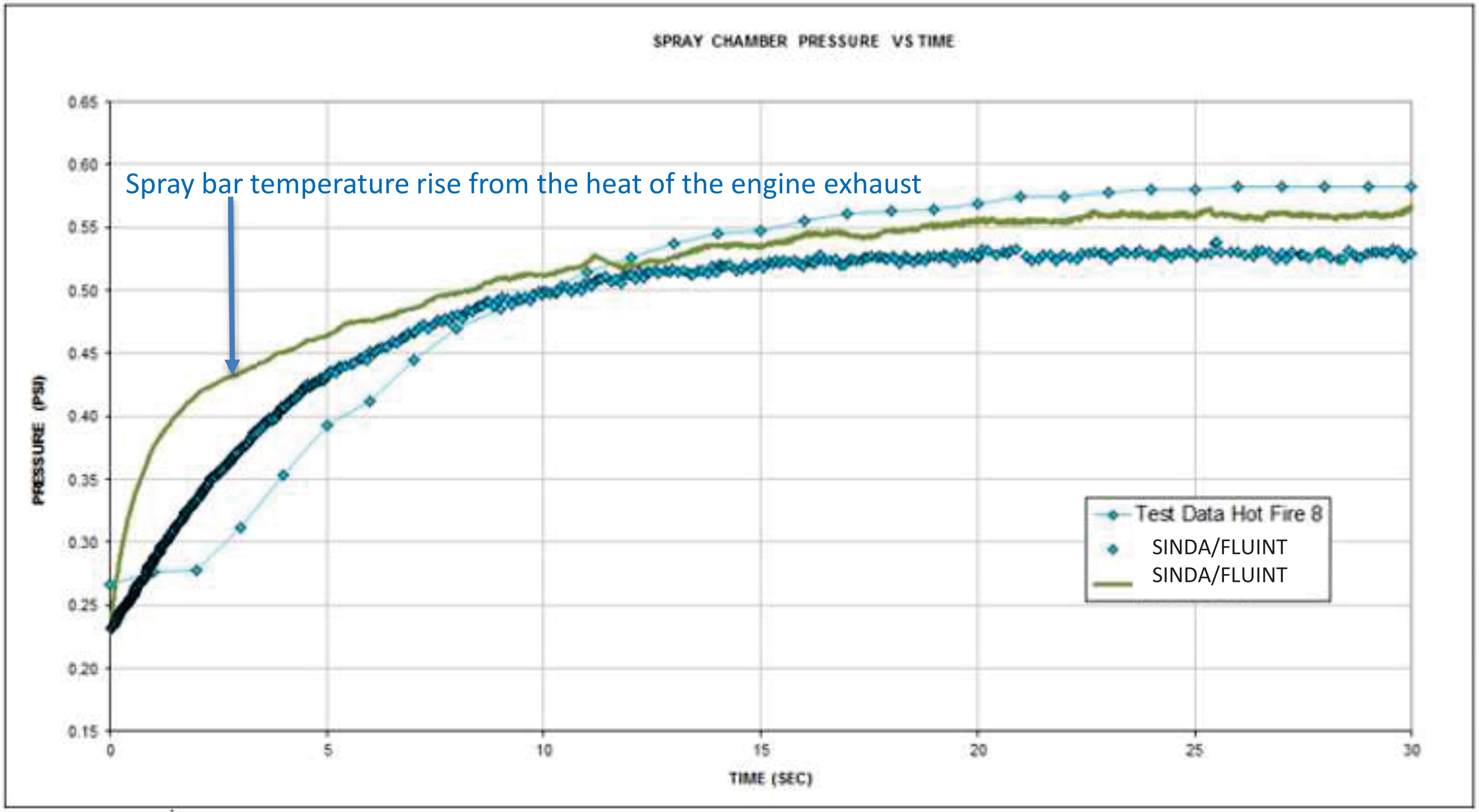


Figure 17: Spray Chamber Pressure: Hotfire Test 8 and SINDA/FLUINT Model Results

Delta III Upper Stage Hot Fire Test and SINDA/FLUINT

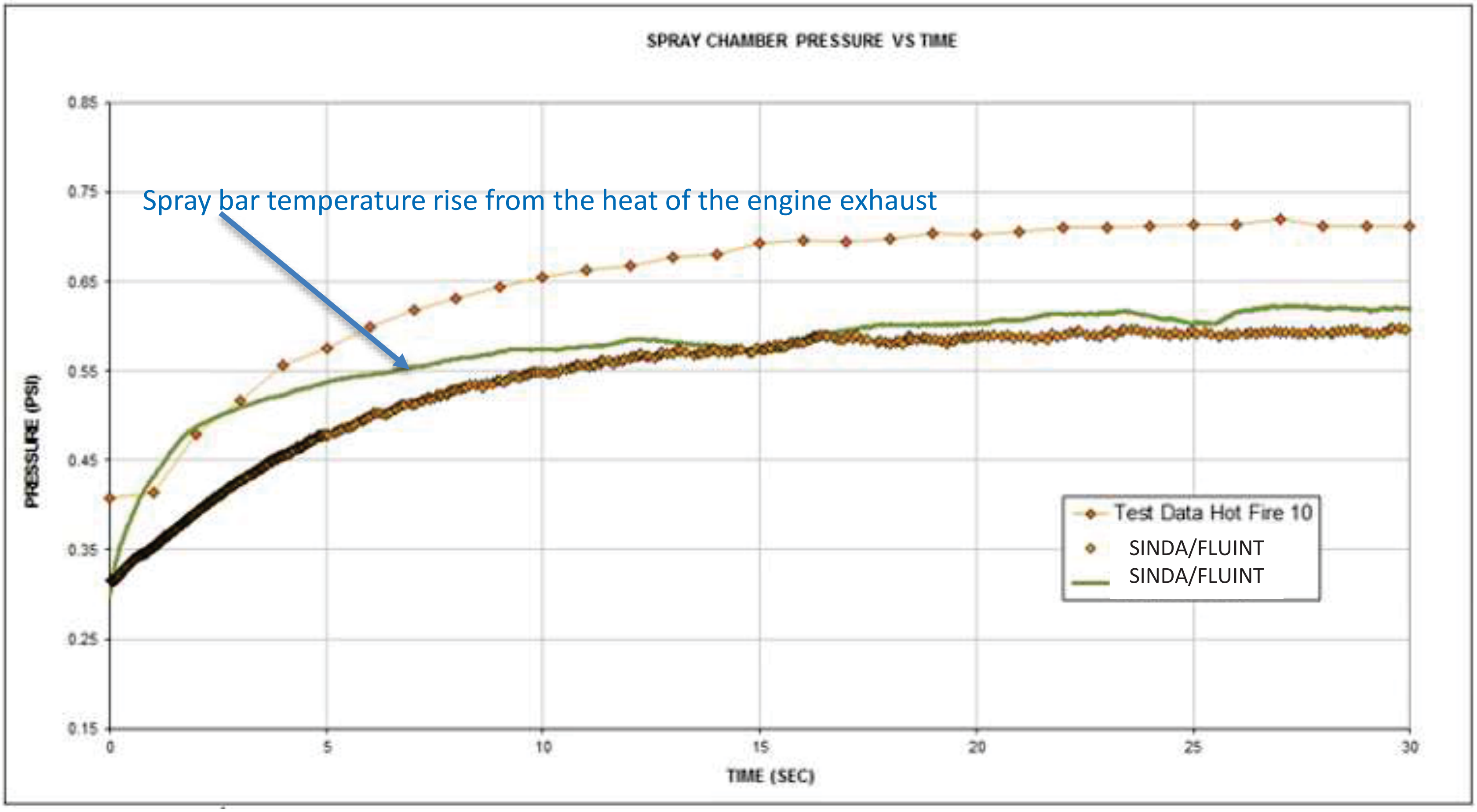


Figure 18: Spray Chamber Pressure: Hotfire Test 10 and SINDA/FLUINT Model Results

Candidate Test Article and SINDA/FLUINT

- Candidate test article larger than the previously conducted engine tests
- Two point engine test sequence lasting for 700 seconds.
- Droplets 1500 microns with an initial velocity 37 ft/sec
- Assumed spray bar water temperature rose due to the effect of engine exhaust heat

	Candidate Test Article, First 400 sec.	Candidate Test Article, Last 300 sec.
CONDENSING SPRAY CONDITIONS		
INLET CONDENSING SPRAY TEMPERATURE (DEG F)*	40	40
INLET CONDENSING SPRAY FLOW RATE (KG/SEC)	13878	13878
WATER LEVEL (FT)	70	70
ULLAGE LENGTH (FT)	49.25	49.25
ROCKET CONDITIONS		
ROCKET EXIT AREA (IN^2)	5627	5627
ROCKET AREA RATIO	243	243
ROCKET O/F RATIO	5.797	5.826
ROCKET COMBUSTION PRESSURE (PSI)	882	637

** For spray bar temperature rise due to engine heat exhaust or ejector heat output this was only an initial condition.*

Figure 19: Summary Table of Candidate Test Article

Candidate Test Article and SINDA/FLUINT

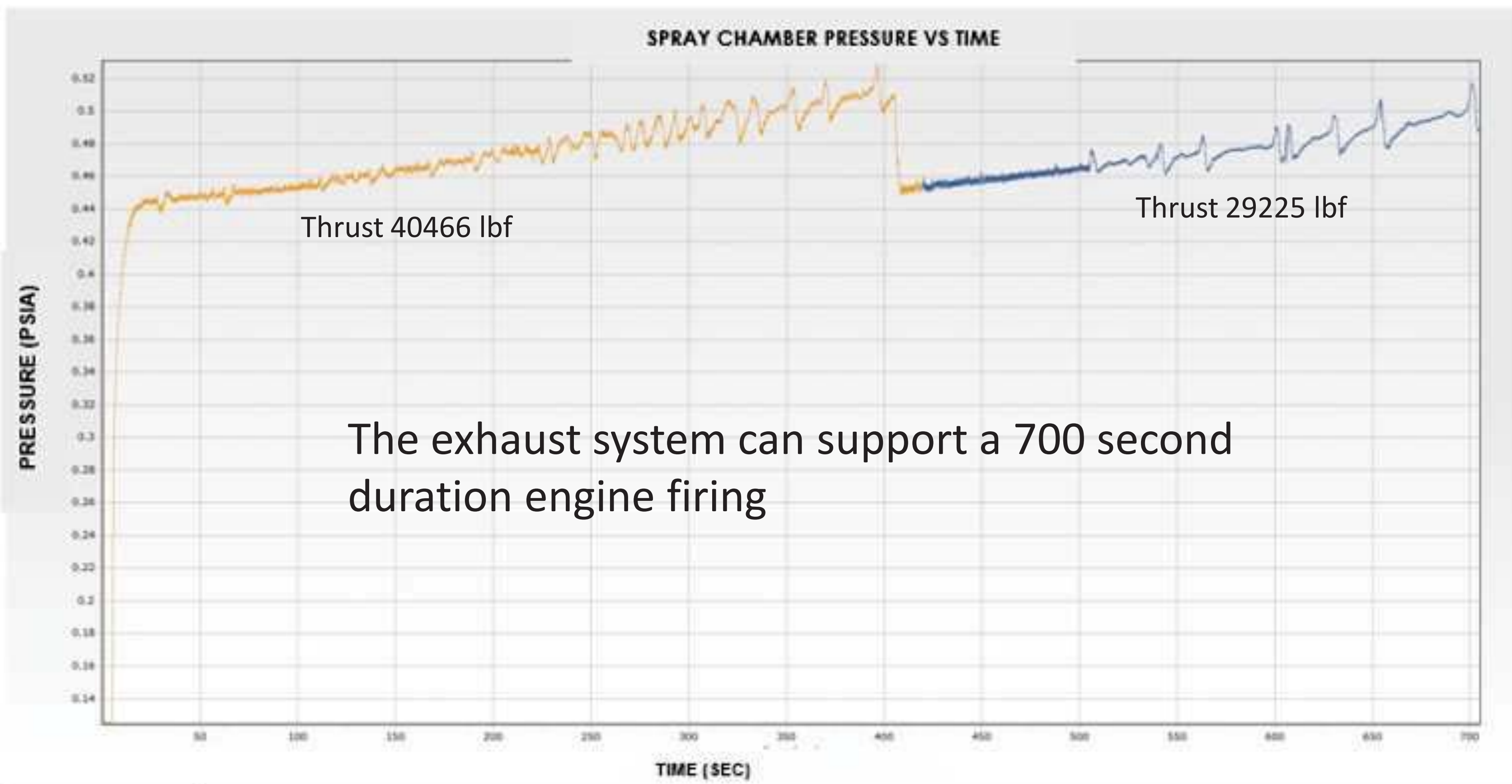


Figure 20: Spray Chamber Pressure: Candidate Test Article and SINDA/FLUINT Model Results

Candidate Test Article and SINDA/FLUINT

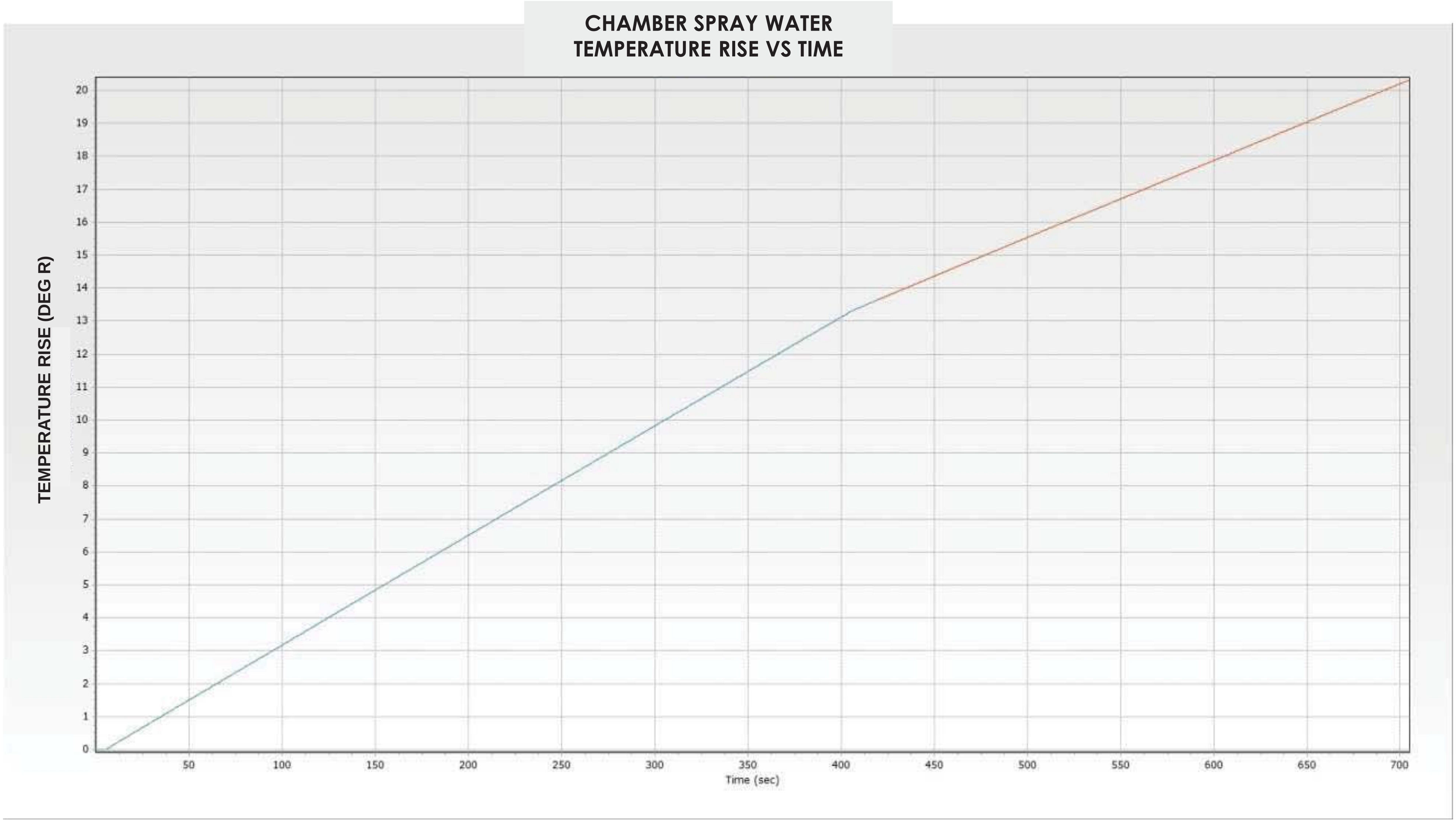


Figure 22: Chamber Spray Temperature Rise: Candidate Test Article SINDA/FLUINT Model Results

Conclusions

- A "solid conduction" model of droplets that correspond to each of the time averaged characteristic droplets is important to capture the physics of a condensing spray chamber.
- The model can be useful in predicting exhaust system performance for various hydrogen-oxygen engine combinations and testing durations.
- Future engine testing at B-2 will provide opportunities to evaluate and refine the model.